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# A Remotely-Operated Facility for Evaluation of Post-Combustion CO<sub>2</sub> Capture Technologies on Industrial Sites

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**Abstract**—ACTTROM (Advanced Capture Testing in a Transportable Remotely-Operated Minilab) is a transportable test facility for bench-scale evaluation of post-combustion CO<sub>2</sub> capture technologies using real industrial flue gases. It is designed to be remote-operable, requiring visits only once per month for maintenance and sample collection. ACTTROM is the first facility of its kind, owned and operated by academia for collaborative research in an industrial environment, and this has resulted in a number of unique developments to facilitate remote operation at an industrial host site. Specifically, it has been necessary to design the unit to automatically correct or mitigate the effects of fault conditions, and to be remotely-monitored via a user interface at 24 hour intervals.

**Index Terms**— CCS, Environmental, Industrial, Remote-operated, Research and Development, Emissions.

## I. INTRODUCTION

Remotely-operated equipment is widely used as a means of sharing educational facilities (e.g. [1], [2]) and occasionally collaborative research equipment (e.g. [3]) between institutions, or where it is desirable to maintain a distance between the apparatus and the operator for experimental [4] or safety reasons. Remote monitoring equipment is also commonly used in fieldwork, for example in climate or weather monitoring, which can significantly reduce operational cost [5]. An intermediate scenario arises when it is desirable to carry out long-duration experiments, using unattended research facilities on large industrial sites. Under these circumstances, it may not be cost-effective to supervise the facility continuously due to the location or the long-term nature of the tests to be carried out. One potential application of unattended remotely-operated laboratories on industrial sites is in the process and power generation industries, which continuously need to improve their environmental performance. By trialing economically promising emissions mitigation technologies at bench-scale using process slipstreams, it is possible to evaluate the performance in a real application after long term exposure to trace impurities, before making the decision to invest in further tests at pilot-scale. ACTTROM (Advanced Capture Testing in a Transportable Remote-Operated Minilab) is primarily designed for evaluation of post-combustion 'Carbon Capture and Utilization' technologies which are used to extract CO<sub>2</sub> from fossil fuel energy generation processes before it reaches the atmosphere. It is contained in a 6062mm × 2438mm × 2052mm



Figure 1. Exterior view of the ACTTROM unit being loaded prior to transport

transportable chemical storage unit (see Fig. 1) and the current prototype is equipped with control systems, a 3G/wifi internet connection, an infrastructure for distributing power plant flue gases between experiments. While some transportable facilities capable of doing this already exist (see [6], [7]), however, it is the first facility of this kind which can be operated remotely leading to better monitoring system and significantly reduce R&D cost.

ACTTROM is owned and operated by the University of Edinburgh and is part of the UKCCSRC (UK Carbon Capture Research Centre) PACT (Pilot Advanced Capture Technology) facilities (see <http://www.pact.ac.uk/>), a set of specialist R&D facilities for combustion and carbon capture research which aim to accelerate the development and commercialization of these technologies. ACTTROM aims to provide services to a number of stakeholders, including academic researchers, commercial technology developers and end users of carbon capture and utilization technologies.

## II. DESCRIPTION OF APPARATUS

### A. Flue Gas Conditioning and Distribution Infrastructure

Flue gas conditioning is necessary firstly to prevent accumulation of condensate in the test system, and secondly to represent unit operations used in large scale carbon capture processes. A simplified diagram of the flue gas conditioning and distribution infrastructure is shown in Fig. 2. The present design is suitable for use with natural

gas power plants, which are low in acid gases and particulates, but high in moisture. Flue gas is drawn into the infrastructure by a Boxer<sup>TM</sup> 3114 diaphragm pump, manufactured by Uno International Limited (UK). The pump is positioned to minimize damage from condensate or corrosive components in the gas. It is controlled by a ES030-5 programmable power supply, manufactured by Delta Electronica (Netherlands).

Pipework upstream of the knockout drum is sized to give a minimal pressure drop, so as to avoid excessive vacuum in the system, which might result in vessel implosion. As a precaution the knockout drum and upstream components are protected by a MP-series vacuum relief valve, rated to 0.05 bar and manufactured by Circle Seal Controls, USA. Since many power plants have multiple power generation units, not all of which run at the same time, ACTTROM is designed to be able to select flue gas streams from up to two sources via one of two actuated ball valves (ABVs - all actuated ball valves in the unit are supplied by J+J automation (UK) and use J2 or J3-type electrical actuators). The flue gas then passes through a spray column which acts as a direct-contact cooler and water wash, removing some of the acid gases (primarily SO<sub>2</sub> and NO<sub>2</sub>) and controlling the humidity, usually dehumidifying. The spray column is a 1 ½ inch NPS (Nominal Pipe Size) stainless steel tube, with internal diameter around 45mm, containing 4mm ceramic saddles to ensure good contacting between the gas and the water. Any water droplets remaining in the flue gas are removed by a knockout drum packed with stainless steel gauze, then allowed to drain into the column liquid outlet line. A non-return valve with low cracking pressure is used on the drain line to prevent flue gas bypassing the spray column, while allowing drainage of water once a sufficient head of water has accumulated. After the knockout drum, a bespoke humidity sensor based on a Honeywell HIH-4000-series sensor chip and a k-type thermocouple is used to measure the condition of the flue gas. The gas flow rate is then measured by a Honeywell AWM5104VN Venturi-type mass air flow sensor. Between the gas intake to the spray column and the outlet of the knockout drum, most vessels and pipework in the flue gas conditioning and distribution infrastructure are lagged to conserve energy and prevent evaporation of mist in the knockout drum. With the present configuration a total flue gas flow rate of 5-8 Litres/minute is possible.

The water used in the spray column is drawn from an inventory tank which is continuously purged to the site drains by adding fresh mains water. The purge is necessary to ensure that the water does not become overly acidified and the rate is set (using a needle valve) at a value which keeps the pH at 5 or higher in order to meet UK environmental protection requirements. Under normal circumstances, purged water is allowed to flow out of a lower overflow line and is topped up by a stainless steel float ball valve via another ABV, however if the lower overflow becomes blocked, the water can escape from the upper overflow. If both become blocked, an automatic shutdown is triggered by a high level switch and water is released from the ABV below the inventory tank. In the event of a drains blockage, the water will overflow into a 2m<sup>3</sup> bund, triggering a level switch, sending an alarm and ultimately triggering an automatic shutdown if no remedial action is taken.

Within the spray column, a full cone spray nozzle, (product code 1/8HH-1, Spraying Systems Ltd., USA) is used to distribute the water over the packing. Pressure and flow are provided by a Micropump L22063 gear pump, also powered by a ES030-5 programmable power supply. Between the pump and the spray nozzle, the water passes through a heat exchanger which is used to reduce the temperature to 5-10°C in order to control the absolute gas humidity at the spray column outlet to acceptable levels, since natural gas combustion generates significant moisture. A Gems Sensors and Controls (USA) Rotorflow<sup>TM</sup> flow sensor (part no. 155420) is used to measure the water flow rate, and this is protected from overpressure by a pressure relief valve which relieves water to upstream of the gear pump. Water temperature is monitored by a k-type thermocouple. After exiting the spray column, the water line merges with the knockout drum drain line and returns to the inventory tank. The level of the base of the spray column is roughly the same as the level of water in the inventory tank, so that the line connecting the two acts as a seal and prevents flue gas passing into the overflows. An inspection port is available on the top of the spray column and is capable of admitting an endoscope of probe diameter 8mm or less.

Downstream of the diaphragm pump, the majority of the flue gas is sent to the test rigs, however a small proportion passes through a Marsh Bellofram (USA) Type 51 pressure regulator, rated for 0-2psi. Part of the bypassed gas is drawn through a combined SB2000 CO<sub>2</sub>/O<sub>2</sub> analyzer by the internal diaphragm pump. The analyzer is supplied and manufactured by ADC Gas Analysis (UK) and is designed to measure CO<sub>2</sub> composition in the range 0-20% and O<sub>2</sub> composition in the range 0-25%. It is not designed to handle pressures above 0.3 bar, and is protected by vacuum and pressure relief valves, rated for 0.05bar and of a similar type to that used on the knockout drum. After the gas analyzer, the bypass merges with the flue gas return line, and is cleaned by an adsorption filter comprising a Headline Filters (UK) 146CC housing containing Chemsorb Multigard<sup>TM</sup> 3800 adsorbent supplied by Molecular products Ltd (UK). In an emergency, gas can be vented from an ABV. Finally the gas mass balance is checked by a second flow sensor, identical to that used at the knockout drum outlet, before return to the sample point the gas was extracted from. A photograph of most of the flue gas conditioning and distribution infrastructure is shown in Fig. 3.

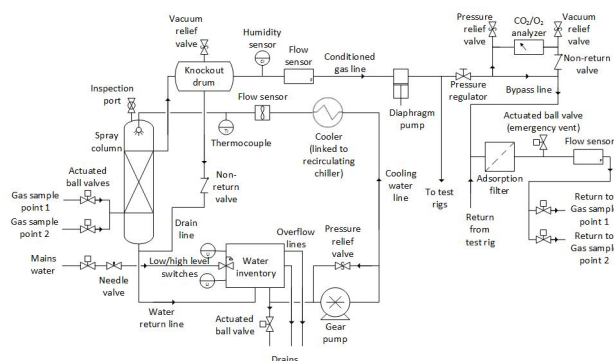


Figure 2. Flue gas conditioning and distribution infrastructure





Figure 3. Photograph of the Flue Gas Conditioning and Distribution Infrastructure showing the knockout drum at on the top shelf, the water inventory tank on the lower shelf and the spray column on the left

### B. Test Rig

The prototype version of ACTTROM uses a single test rig (see Figs. 4 & 5), designed for batch-testing of carbon capture solvents in order to test their resilience to chemical degradation. Most carbon capture solvents are based on amines or amine blends which are optimized for a particular application based on properties such as viscosity, CO<sub>2</sub> capacity and regeneration energy - the enthalpy required to release the CO<sub>2</sub> in a pure form so that it can be pressurized and safely stored in geological formations, while allowing the solvent to be re-used.

The flue gas used by the test rig is removed from the conditioning and distribution infrastructure at a rate controlled by a MC-100SLPM-D/5M mass flow controller supplied and manufactured by Cole Parmer Instrument Company Ltd (UK branch), which was selected for its low pressure drop. The test rig can be isolated by a solenoid valve when the system is in the shutdown state and back-flow is prevented by a non-return valve. A bespoke manifold, made by welding 'air stones' (sintered stainless steel cylinders) to a distribution tube, was used to disperse the flue gas in the solvent tank. The temperature in the solvent tank is controlled by a heating coil containing deionized water, which is connected to a 'Temperature Controlled Recirculator' (TCR) of the same type as is used for chilling, as described in section C. Temperature in the tank is measured as the average of two k-type thermocouple probe readings on opposite sides of the tank and controlled by the TCR using a PID loop. If the pressure in the solvent tank exceeds 0.05 bar, gas can escape via pressure relief valve leading to an external vent while the control

system reacts to the problem. An OEM FS5 thermal mass flow indicator and evaluation board, both manufactured by Innovative Sensor Technology (Switzerland), were used to output a voltage which indicated flow when it fell outside the normal range. This approach was taken because of the potential exposure of the sensor to a corrosive environment, meaning that cheap and easy replacement was desirable, and because it was only necessary to determine when the flow was non-zero. The relief line pressure, and hence the tank pressure, is measured by a pressure transducer capable of measuring both pressure and vacuum, allowing triggering of a warning and then a shut-down when the pressure falls outside low and high deviation alarms. Solvent sampling is possible via a Minimes<sup>TM</sup> sample point supplied by Hydrotechnik UK Ltd, which was designed to eliminate leakage and hence be suitable for remote operation.

Due to the risks associated with solvent accumulation or loss, robust level control is an important requirement for the test rig. Hydrostatics is used to measure the solvent mass in the solvent tank, and hence determine the level, by two high-resolution pressure transducers supplied by Omega Engineering Ltd. (UK branch), Model PXM319-0.07, with range 0-1psi. Calibration was carried out by correlating the difference in output currents directly with the known mass of water in the tank. The pressure transducers are the primary means of controlling the level of liquid in the tank. When the mass of solvent falls below a threshold value, deionized water is released from a top-up tank via a solenoid valve, diluting the solvent. The rate of water consumption is monitored by an LVR31 level transmitter, also supplied by Omega Engineering Ltd, and a separate float switch indicates when the tank is empty. A u-bend on the top-up line reduces the likelihood of flue gas escaping, and the top up tanks are connected to vents external to the unit to reduce the risk of harm to any operators present. When the primary top up tank is exhausted, or if the line becomes blocked, and the level falls below an acceptable value indicated by a low level switch, the solvent level is maintained by a reserve top-up tank. In the event of water accumulation, a minor fault will be indicated by a high level switch. A more serious fault, indicated by a 'very high level switch' will require the remote operator to verify that the apparatus is safe every 48 hours to prevent a shutdown. If the solvent tank is full, liquid can pass into an overflow tank and a level switch will indicate when this contains more than a few mm of solvent. Should the high level switch in the overflow tank be triggered, the system will shut down immediately.

Flue gas exiting the solvent tank passes into a reflux condenser, which returns most of the water and other evaporated degradation products to the solvent tank. The condenser was manufactured in-house and uses eight 'cold fingers' – concentric tubes where the external tube is sealed at one end and the inner tube is slightly shorter, allowing fluid to flow in through one tube and out through the other – containing a coolant. The cold finger external diameter is ½ inch and the external shell diameter is 4 inch. Droplet knockout is achieved using stainless steel mesh packing, in a similar manner to the knockout drum. After leaving the condenser, some of the gas is drawn into a parallel stream for analysis by a humidity sensor and gas analyzer of the same types as are used in the conditioning and distribution infrastructure. This makes it possible to establish when the system is at equilibrium, i.e. the solvent



Figure 4. Photograph of the test rig, showing the solvent tank on the lower shelf, the condenser on the middle/upper shelf and most other components on the upper shelf

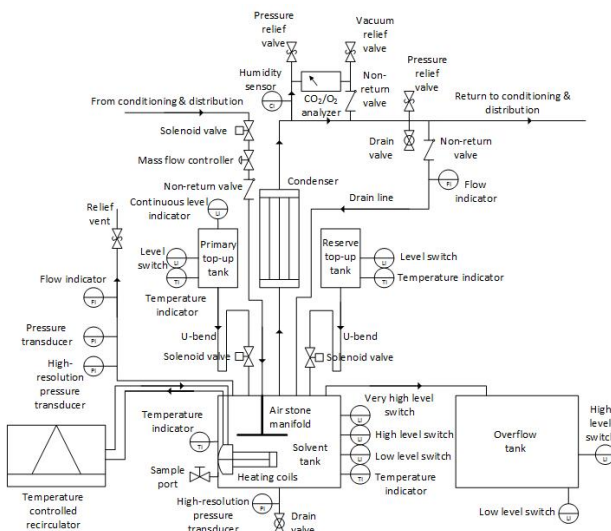


Figure 5. Solvent test Rig

is fully loaded with CO<sub>2</sub> and the inlet and outlet flue gas humidities are equal, by comparison with the inlet gas composition. Should any mist or condensate carry over from the condenser, a drain line and manual drain valve are installed at a low point in the flue gas outlet line. The drain line returns directly to the solvent tank via a non-return valve which opens when a large enough head of liquid has accumulated. If the non-return valve sticks open, the outlet flue gas can potentially bypass the condenser and a second FS5 thermal mass flow indicator is installed to warn of this. In the event of a blockage, most likely to be caused by accumulation of condensate, a 0.05 barg pressure relief valve of the Circle Seal MP type allows the flue gas to relieve to an external vent in the same manner as for the other gas pressure relief valves. After leaving the test rig system, flue gas is returned to the conditioning and distribution infrastructure.

### C. Temperature Controlled Recirculator (TCR) Loops

Two Model 5350 Temperature Controlled Recirculators (TCRs), manufactured by Polyscience (USA), are used to cool the condenser in the test rig and the water passing through the heat exchanger in the flue gas conditioning/distribution infrastructure. The cooling fluid is 50% aqueous monopropylene glycol, which was chosen for its low freezing point and low toxicity. Under normal circumstances the TCR loops are isolated from each other and cool each system separately, however if one of the chillers fails, the other can cool both the heat exchanger and the condenser. This reduces the impact of failure of the cooling systems on the water balance, mitigating the resulting risks while the problem is corrected. Furthermore, by positioning the heat exchanger upstream of the condenser in the new flow path, the inevitably reduced condensation rate can be corrected for by the top-up tanks. If the system were to accumulate moisture due to excessive inlet flue gas humidities, no correction could be made. Limited control of the flow rate on each TCR is possible by partially opening the proportioning solenoid valves to bypass some of the fluid. The operation of the TCR loops is shown in Fig. 6.

## III. CONTROL AND MONITORING SYSTEMS

### A. Network Components

ACTTROM connects to the internet using a Proroute H685 industrial 3G router containing a fixed IP SIM card supplied by Anvil Communications Ltd (UK). The fixed IP sim allows easy connection to most Windows<sup>TM</sup> systems via Remote Desktop, while the industrial router improves the security of the connection. The Ethernet connections internal to the unit are made via a SDI550 unmanaged 5-port Ethernet Switch manufactured by Westermo (UK subsidiary). This connects to a PAC (Programmable Automation Controller) and a host laptop. The laptop is a Dell Latitude<sup>TM</sup> 6430 ATG Ruggedized model and the PAC is a CompactRio 9022, manufactured by National Instruments Corporation (USA). All of the network components are selected to withstand a minimum temperature of -20°C or less.

### B. Control and Data Acquisition Systems

The current prototype version of ACTTROM is capable of functioning with a single CompactRio PAC with slots for eight I/O (Input/Output) modules:

- 1× NI9425 32 channel digital input (ABVs, float switches and Rotorflow sensor)
- 1× NI9476 32 channel digital output (ABVs and solenoid valves)
- 3× NI9207 8 current channel + 8 voltage channel analog input (pumps, gas flow indicators and gas analysis)
- 1× NI9264 16 channel analog voltage output (pumps)
- 1× NI9214 16 channel thermocouple input
- 1× NI9870 4 port RS232 serial communication (mass flow controller and TCRs)

Additional I/O modules, would be accommodated in extension chassis or additional controllers.

Most of the I/O, with the exception of the thermocouples serial devices and programmable power supply con-



trols, could not practically be connected to the modules directly. A junction box containing two 500mm DIN rails was therefore set up to accommodate the connection terminals and most of the power supplies. Because the various analog devices operated at two different voltages (5V and 10V), and the programmable power supplies used floating outputs, it was necessary to use three separate analog modules. Furthermore, the CO<sub>2</sub>/O<sub>2</sub> analyzer current outputs were powered directly from the device and not via the loop: since each output had a different ground potential, isolation amplifiers needed to be used when connecting them to the analog I/O. A schematic diagram of the control, monitoring and data acquisition systems is shown in Fig. 7.

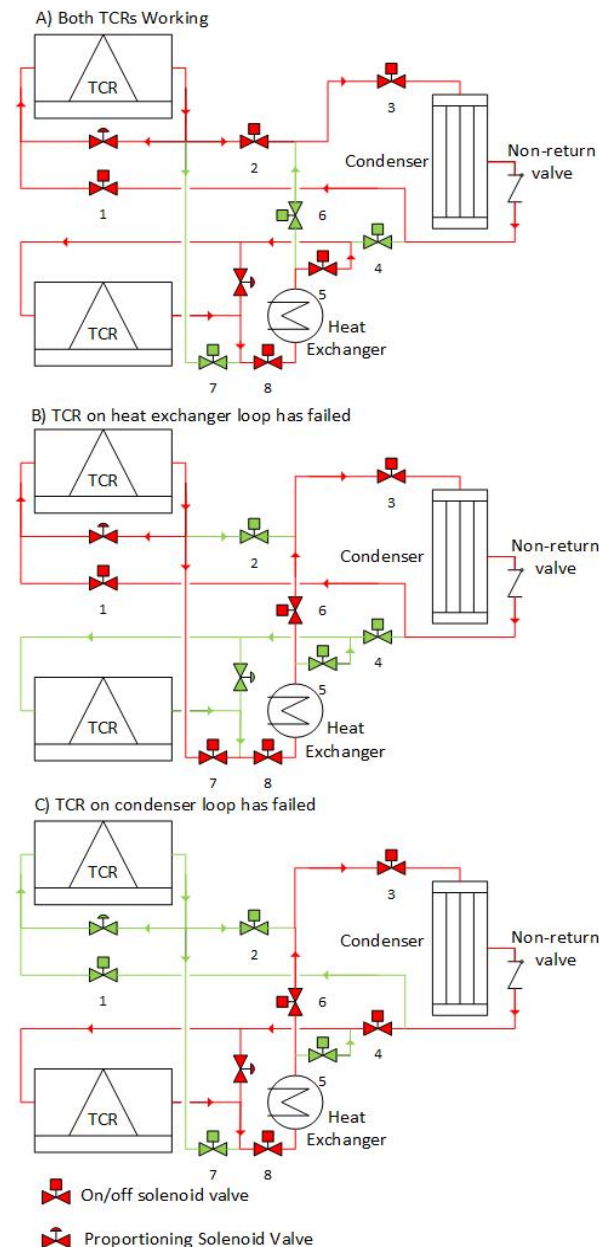


Figure 6. Operation of the Temperature Controlled Recirculators (TCRs) in ACTTROM, showing: A) The normal running state; B) The running state if the TCR on the heat exchanger loop has failed; and C) The running state if the TCR on the condenser loop has failed. Valves which are open and lines which are running are shown in red. Valves which are closed and lines which are not running are shown in green.

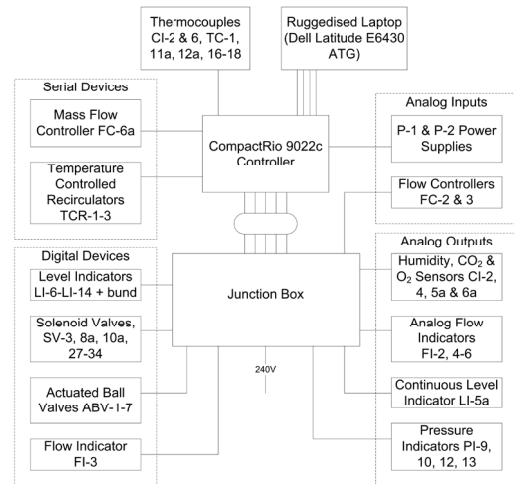


Figure 7. Control, monitoring and Data Acquisition Systems

As well as being used to host and program the PAC, the Dell Laptop is used to host the user interface (Fig. 8) for remote monitoring of the unit. If the Laptop fails for any reason, the PAC will usually continue to run autonomously using the last settings it received, meaning that the test will not necessarily be invalidated.

#### IV. SAFETY, CONTROL AND MONITORING

##### A. General Safety Requirements

It was agreed that the primary method of fire prevention would be to eliminate flammable vapors by ventilating the unit, with a mean air residence time of 5 minutes. This was achieved using two exhaust fans which were installed over existing vents in the storage unit. Twelve Fireblitz™ frangible bulb-type FE36 gas fire extinguishers with an activation temperature of 79°C were installed as a second line of defence. The fire alarm system had a battery back-up and was designed to trigger an automatic cutoff of the main power supply to the unit in order to prevent secondary damage to the unit from live electricity, as well as to shut off the ventilation fans and prevent dispersal of the FE36 gas. As a final precaution, the main electricity supply was fitted with an external emergency cutoff button so that staff at the industrial host site could neutralize the unit in the event of a dangerous occurrence that the control systems were unable to prevent.

Since the unit was designed for use in Northern Europe, adequate protection from low temperatures was essential. Based on energy balances and historical weather records for potential deployment locations, two 3kW thermostatic convection heaters were purchased. A section was also included on the monthly inspection checklist for use after a cold period.

All procedures to be used in the unit had to be clearly defined and documented as 'Safe Systems of Work' (SSWs), together with supporting general risk assessment and COSHH (Control of Substances Hazardous to Health) assessment forms. Previous safety assessments, including a HAZOP and a PPC report also needed to be retained.

##### B. Programming

The CompactRio PAC was programmed using Labview 2013 and with the controller in Scan Mode. Network Shared Variables are used to transfer information between the PAC and the user interface on the host laptop.

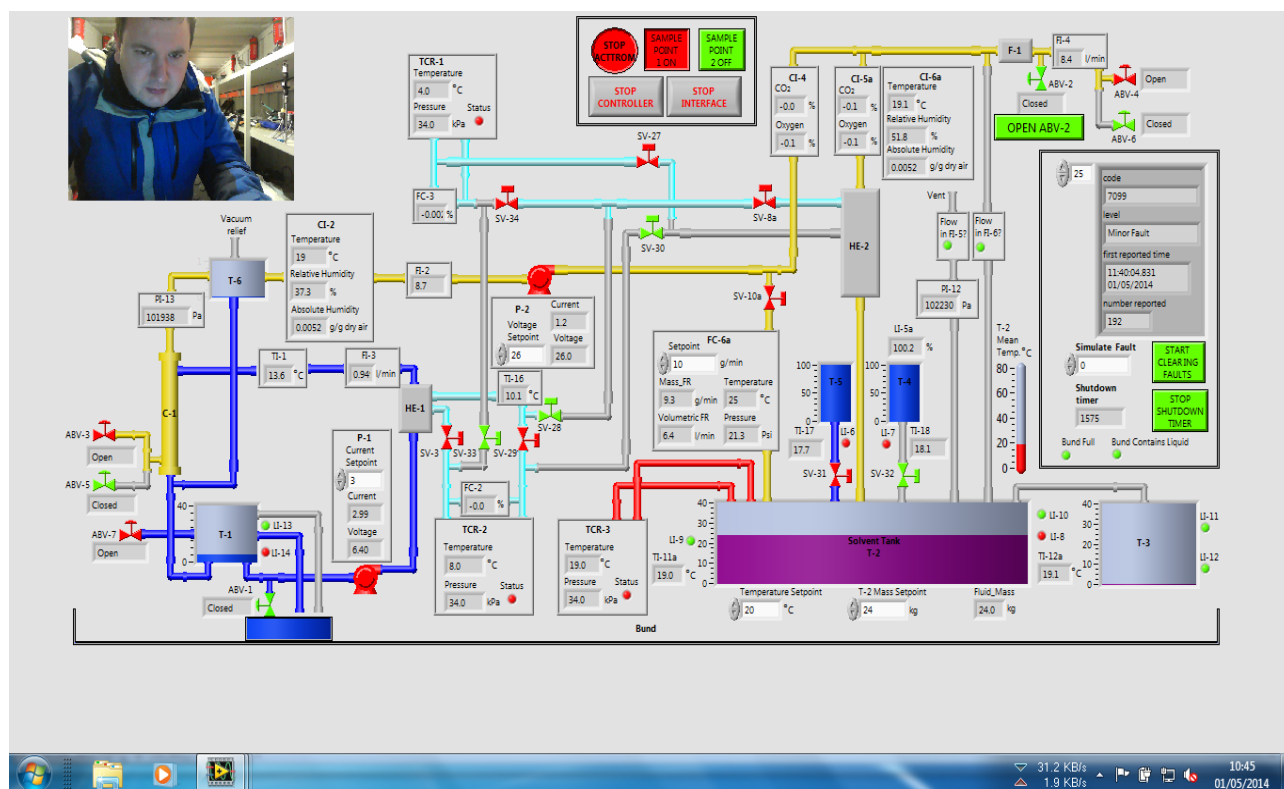


Figure 8. ACTTROM User Interface

On the PAC, most of the control actions are carried out using a State Machine architecture and the operation of this is described in Fig. 9. Due to timing issues, the Rotor-flow sensor and the serial devices need to be run in separate loops to the main state machine, however variables are shared between the loops where necessary.

In general, the program carries out a repeated sequence of actions in one of three states: Shutdown, Standby or Normal Running. In Shutdown state, all devices are repeatedly forced into a safe condition and the 'Run ACTTROM' button on the front panel is forced into the off position. All other instrumentation is monitored to ensure that the rig remains safe and Fault codes are sent to the user interface (see box on right hand side of Fig. 8) when values deviate outside acceptable limits. These limits can vary depending on the running state, and a different first digit is used for fault codes in each state (5xxx for Shutdown, 6xxx for Standby and 7xxx in Normal Running). A reference table describing each Fault Code is kept in the unit. The Standby state is similar to the Shutdown state, except that the water inventory tank is kept full and the solvent tank is maintained at its setpoint temperature. Standby is used to allow rapid progression to the Normal Running state, which is desirable when the host plant is providing flue gas intermittently for short periods, as is typical of Gas power stations when they are used to back up intermittent renewables. Progression from Shutdown to Standby is initiated by pressing the 'Run ACTTROM' button on the user interface. At present, progression from Standby to Normal running is actioned by pressing either of the Sample Point buttons, however when the unit is deployed these will be replaced by an automatic trigger such as a thermocouple reading or a digital output from the power station control system.

The transition to the Normal Running state progresses through a series of events in order to reach the desired operating condition. To begin with, ABVs are set to the desired position, depending on which sample point is in use. When the limit switches on the ABVs indicate that the valve positions are correct, the pump speeds are gradually increased to the setpoint values, completing the transition. Once the Normal Running State is reached, the system is able to react to undesirable operating conditions or component failure by:

1. Sending Fault Codes to the user interface;
2. Changing the operation of the TCRs;
3. Sending a request to the remote user to reset a timer every 48 hours after verifying that the system is safe;
4. Shutting down the system if a fault persists after a set period of time; or
5. Shutting down the system instantly.

Fig. 9 uses the following abbreviations in addition to those previously defined:

- AI:** Analog input
- CI:** Composition indicator (gas analyzer or humidity sensor)
- DI:** Digital input
- DO:** Digital output
- FI:** Flow indicator
- LI:** Level indicator (or level switch)
- MFC:** Mass flow controller
- PI:** Pressure indicator (transducer)
- SV:** Solenoid valve
- TI:** Temperature indicator (thermocouple)

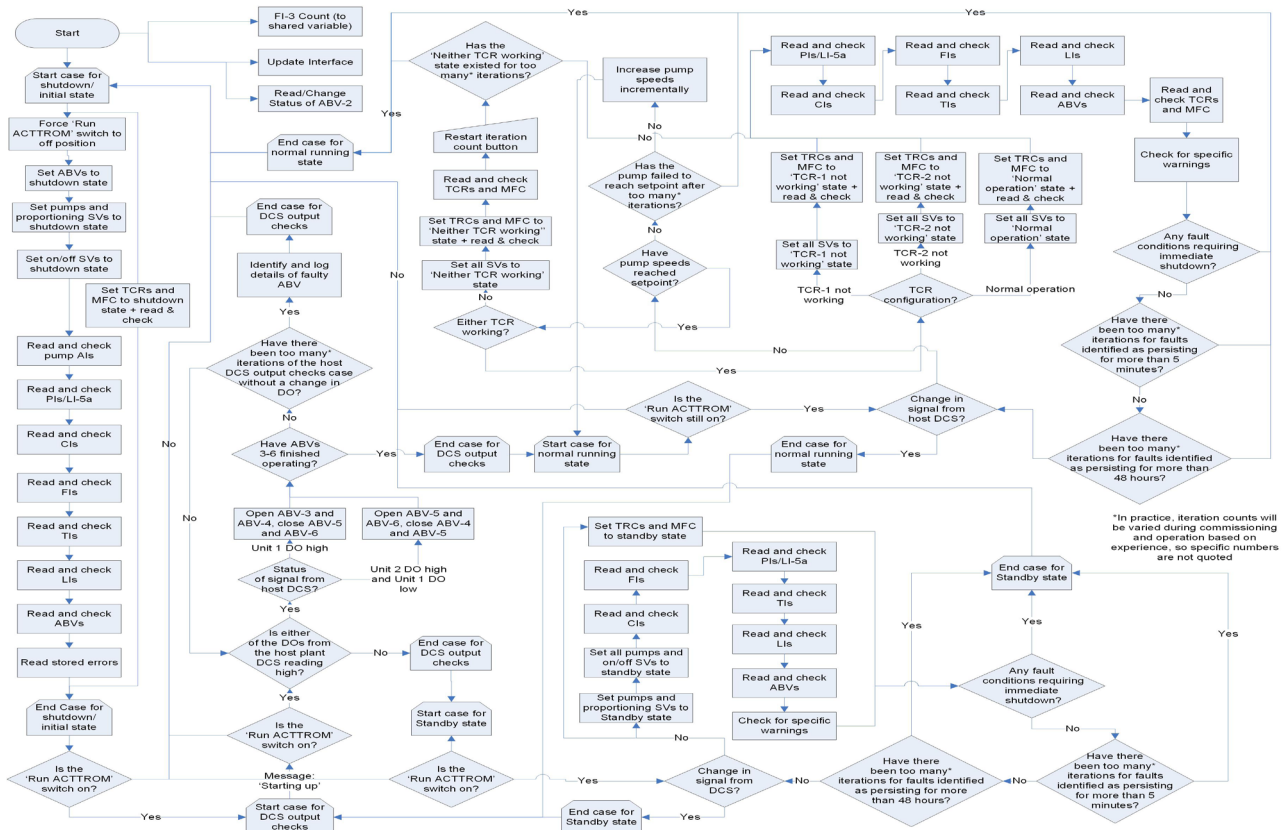


Figure 9. Program flow diagram

### C. Monitoring and Site Visits

Once deployed, remote monitoring of ACTTROM will be necessary on a daily basis and will be carried out by using remote control software to connect to the host Laptop, then checking the user interface. Log sheets have been designed and will be used to track the performance of the system over an extended period of time. The daily logging sheets also require that the gas pressure reading downstream of the spray column and the pressure at the MFC outlet be recorded. These can provide important information about the performance of the diaphragm pump, possible fouling or flooding in the spray column and blockage or breakage of the air stone manifold.

Monthly site visits allow sample extraction and necessary maintenance of the unit, such cleaning of the dust filters in the TCRs. A monthly inspection checklist has been developed to ensure that all routine maintenance, equipment checks and sampling actions are taken. In addition, a monitoring form is appended to ensure that the adsorbent in the adsorption filter is changed before it becomes saturated. Safe Systems of Work are available for all standard tasks to be undertaken during monthly visits where there is a known hazard. For example, a procedure for safe entry to the unit and correct use of a portable gas monitor, which was purchased to facilitate this, was developed. If any other maintenance according to procedures not agreed in advance by the host site needs to be carried out, standard site rules for approving the procedure must be followed.

### V. TEST RESULTS

ACTTROM has been tested over a period of two weeks with atmospheric air + 30 wt% MEA (monoethanolamine)

to test its long term resistance to degradation. Several operational parameters listed in Table 1 were recorded for further analysis and to aid optimization of the CO<sub>2</sub> capture process. Degradation products of MEA will also be investigated [8]. Remotely-monitoring was carried out at 24 hour intervals, and the results indicated that ACTTROM performed safely under remote real-time monitoring. For instance, in some high risk operational conditions, ACTTROM has been demonstrated to be able to remotely shut down/restart via the 3G/wifi connected devices.

TABLE I.  
ACTTROM OPERATING PARAMETERS

Parameter	Description	Unit
PI-13	Pressure at water spray column	Pa
TC-6	Temperature at humanity sensor (inlet)	°C
CI-2 %RH	Inlet flue gas relative humanity	%
CI-2 AbsH	Inlet flue gas absolute humanity	g/(g dry air)
FI-2 Flow rate	Inlet flue gas volumetric flow rate	l/min
FC-6 Pressure	Capturing reactor pressure	Psi
FC-6 Mass Flow rate	Flue gas mass flow rate	g/min
FC-6 Vol Flow rate	Flue gas volumetric flow rate	l/min
CI-4 CO <sub>2</sub>	Flue gas CO <sub>2</sub> composition	%
CI-4 O <sub>2</sub>	Flue gas O <sub>2</sub> composition	%
(TC1+TC2)/2	Capturing reactor temperature	°C
CI-5 CO <sub>2</sub>	Emission gas CO <sub>2</sub> composition	%
CI-5 O <sub>2</sub>	Emission gas O <sub>2</sub> composition	%
TC7	Temperature at humanity sensor (outlet)	°C
CI-6a %RH	Outlet flue gas relative humanity	%
CI-6a AbsH	Outlet flue gas absolute humanity	g/(g dry air)
FI-4 flow rate	Outlet flue gas volumetric flow rate	l/min



## VI. CONCLUSIONS

A remotely-operated facility for evaluating emissions mitigation technologies at bench scale on industrial sites has been developed and tested. Important aspects of the development process included the physical hardware design/selection, programming of control systems and documentation of the facility. All of these aspects were informed using industrial hazard studies, so that the resulting facility would meet the safety requirements of an industrial host site. The resulting design incorporated numerous features which would not usually be necessary for Remote Laboratories in a university or college environment, enabling it to handle adverse ambient conditions and a delayed human response, while minimizing the risk to the reputation of the host site. It is envisaged that the development of ACTTROM will inform the development of similar facilities in future.

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